IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Applicant: Etsion et al.	§	
Serial No.: 10/541,754	§	
Filed: July 8, 2005	§	Group Art Unit: 3682
For: Laser Surface Textured Fluid-Film Bearing	§	Attorney Docket: 755/23
Examiner: Lenard A. Footland	§	

Commissioner of Patents and Trademarks
Alexandria, Virginia 22313

AFFIDAVIT OF IZHAK ETSION UNDER 37 CFR 1.132

I am presently employed at the Technion -- Israel Institute of Technology as Professor of Mechanical Engineering and the Head of the Shamban Tribology Laboratory. I received my D.Sc. from the Technion in 1974. In 1996, I became a full professor of Mechanical Engineering at the Technion.

I have authored or co-authored over 120 papers, journal articles, and publications in the field of tribology, many of which relate to micropore texturing of seal and bearing surfaces. These publications include chapters of books, relating to tribology:

1. I. Etsion, "Mechanical Face Seals", Chapt. 27 in Mechanical Design and Systems Handbook, Ed. H.A. Rothbart, McGraw-Hill, New York, 1985.
2. I. Etsion and B.M. Steinetz, "Seals", Section 17 in Mechanical Design Handbook, Ed. H.A. Rothbart, McGraw-Hill, New York, 1996.

3. I. Etsion, G. Halperin, and G. Ryk, "Improving Tribological Performance of Mechanical Components by Laser Surface Texturing" in Hydraulic Failure Analysis: Fluids, Components, and System Effects, Eds. G. E. Totten, D. K. Wills and D. G. Feldmann, ASTM STP 1339, 2001

I am a reviewer for the following publications and associations:

Applied Mechanics Reviews
Applied Physics A
ASME Jour. of Applied Mechanics
ASME Jour. of Tribology
ASME Jour. of Fluid Engineering
International Jour. of Solids and Structures
Jour. of Materials Research
Jour. of the Mechanics and Physics of Solids
Proc. IMechE Jour. of Engineering Tribology
Tribology Transactions
Tribology International
Tribology Letters
Wear

German-Israel Foundation for Scientific R&D (GIF)
Israel Ministry of Science
Israel-U.S. Binational Science Foundation (BSF)
National Science Foundation (NSF)

I have reviewed patent application serial number 10/541,754, of which I am a co-inventor, as well as patent number 5,952,080 (Etsion '080), of which I am also a co-inventor, and 6,341,782, of which I am the (sole) inventor. I have also reviewed the Office Action from the USPTO, mailed January 30, 2006.

I would like to clarify the following points:

(1) As elaborated in pending patent application serial number 10/541,754, Etsion '080 does not disclose opposing, load-bearing surfaces having an equivalent clearance convergence between the opposing surfaces.

In Etsion '080, the micropores are evenly distributed over the entire "bearing" surface and are disposed at a distance from each other. In this case, there is – deliberately -- no interaction between neighboring micropores, rather, each micropore acts as an individual micro-hydrodynamic bearing when relative sliding takes place between the opposing parallel surfaces of the bearing. This configuration provides a small load capacity between the opposing surfaces, hence, the primary application is in seals, where small clearance is an essential criterion for good sealing.

(2) My pending patent application serial number 10/541,754 discloses an efficient hydrodynamic bearing with a high load capacity and a much larger clearance as compared with the art disclosed by Etsion '080. The mechanism is not an "individual effect" of a plurality of micropores acting as individual micro-hydrodynamic bearings, but rather, a "collective effect" of the micropores, so as to provide an equivalent converging clearance in the relative sliding direction of the bearing surfaces.

(3) Because the physical mechanism of the inventive bearings is radically different from the physical mechanism of the bearings disclosed by Etsion '080, it was far from obvious, prior to modeling, developing and solving the equations, and experimental testing, that the bearing surfaces of the instant invention would even work, let alone provide superior performance to the cited prior art.

This point was developed in the instant Specification, page 3, line 30 – page 4, line 13.

(4) As an expert in the field of tribology, and more specifically, in micropore-textured tribological surfaces, I would further like to clarify that even if it were known that micropore-textured surfaces may be potentially appropriate for thrust bearing applications – which is not at all obvious, and was not even obvious to me or to my colleagues specializing in micropore-textured tribological surfaces, it would certainly be beyond the realm of one of ordinary skill in the art to design a functional, practicable thrust bearing, a design that must take into account various physical properties of the individual micropore, the position and area density of the micropores on the bearing surface, and the duty and dimensions of the bearing. Moreover, prior to my pending patent application, there existed no theoretical model for understanding the behavior of hydrodynamic bearings having micropore-textured surfaces and in which the clearance force is generated by equivalent clearance convergence between the opposing surfaces.

Without a strong, well-developed theoretical model, and given the large number of parameters that effect bearing performance, identifying the various requisite structural parameters for effective bearing performance is like finding a needle in a haystack, and is certainly well beyond the abilities of one skilled in the art, or even one who is an expert in the art.

(5) By way of example, I have provided herein a copy of a journal article from WEAR (Volume 254, Elsevier (2003) pp. 356–363) pertaining to dimpled tribological surfaces, authored by experts in the field of tribology. The

work described in the paper is purely experimental by trial and error approach with regard to the texturing parameters. Fig. 9 in the paper summarizes results of the friction coefficient for textured surfaces at representative test conditions of 1.2 m/s sliding speed and normal load of 490 N. The friction coefficient of the non-textured surface is shown with a broken line. This figure implies that arbitrary selection of texturing parameters of micro-dimples can succeed or fail in friction reduction. As can be seen from Fig. 9, even in cases of successes with the arbitrary selected texturing parameters, the reduction in friction coefficient is small. This reduction is much less than the about 50% reduction that can be obtained when the texturing parameters are optimized by a theoretical model.

I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further, that these statements with the knowledge that the making of wilfully false statements and the like is punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and may jeopardize the validity of any patent issuing from this patent application.

24 May, 2006
DATE

Izhak Etsion

Izhak Etsion

Curriculum Vitae

Izhak Etsion

Academic Degrees:

1964:	B.Sc., Technion, Israel Institute of Technology
1971:	M.Sc., Technion, Israel Institute of Technology
1974:	D.Sc., Technion, Israel Institute of Technology

Academic Appointments:

1974:	Lecturer, ME Department, Technion.
1976:	Senior Lecturer, ME Department, Technion.
1983:	Associate Professor, ME Department, Technion.
1985-1986:	Visiting Professor, ME Department, UC Berkeley, California.
1996:	Professor, ME Department, Technion
2005:	Visiting Scholar, MIE Dept. Northeastern Univ., Boston, MA, and MAE Dept. UC San Diego, CA

Professional and Research Experience:

1964-1966:	Design engineer, Israel Air Force.
1967-1970:	Research engineer, Center of Aeronautical Research, Technion.
1970-1971:	Manager, technical office, Vulcan Engineering Ltd.,
1975-1976:	Research Associate, NASA-LeRC Cleveland, Ohio.
1979-1980:	Senior Research Associate, NASA LeRC, Cleveland, Ohio.
1996 – present:	Director (Founder) and Chief Scientist, SurTech Ltd.

Technion Posts

1991- present	Head, Shamban Tribology Laboratory,
1997-1998:	Member, Committee for Academic Development.
2001–2003:	Member and Chairman (2003), All Technion Joint Faculty Students Committee.
2002–2005:	Member, Senate committee for undergraduate and graduate studies.
2005-present:	Member, Managing Committee the Russell Berrie Institute of Nanotechnology

Public Professional Activities (Israel):

1982:	Chairman, Organizing committee 16th Israel Conference on Mechanical Engineering.

1983: Member, Organizing committee 17th Israel Conference on Mechanical Engineering.
1984-1985: Chairman, Israel Society of Tribology.
1987: Organizer, International Tribology Workshop, 21st Israel Conference on Mechanical Engineering.
1997: Member, MEMS committee, Israel National Academy of Sciences.
1998–1999: Chairman, ASME International, Israel Section.

Public Professional Activities (International):

1990-1996: Associate Editor, Trans. ASME Journal of Tribology.
1994-2000: Member and Secretary (1999–2000), Executive Committee Tribology Division of the ASME.
1996-1998: Chairman, ASME Tribology Division, International Coordination Committee.
2000 – 2003: Member and Chairman (2002-2003), ASME Tribology Division Nomination and Oversight Committee.
2001–2002: Member, Planning committee of the 3rd World Tribology Congress.
2001–2002: Member, Scientific Committee 3rd AIMETA International Tribology Conference
2004-2005: Member, International Advisory Board of World Tribology Congress III
2005- Member, STLE Fellows Committee

Professional Associations

1. Fellow, American Society of Mechanical Engineers.
2. Fellow (life), Society of Tribologists and Lubrication Engineers.
3. Member, Israel Society for Tribology.

Prizes and Awards:

1. 1984 D.D. Ben-Aharon Research Prize (Technion)
2. 1989 H. Gutwirt Research Award (Technion)
3. 1991 STLE/STC Fluid Sealing Research Award
4. 1998 Academia Romana Traian Vuia Prize
5. 1999 The Hershel Rich Technion Innovation Award
6. 2004 Sanford Kaplan Prize in Creative management for 21st Century High Technology
7. 2005 STLE International Award
8. 2005 ASME Tribology Division Innovative Research Award

Publications and Patents:

More than 120 technical publications in scientific archival journals in the field of tribology, and 15 patents on various aspects of tribology.

Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
ELSEVIER
Wear 254 (2003) 356–363
WEAR
www.elsevier.com/locate/wear

Effect of surface texturing on friction reduction between ceramic and steel materials under lubricated sliding contact

Manabu Wakuda [a,*], Yukihiko Yamauchi [b], Shuzo Kanzaki [b], Yoshiteru Yasuda [c]

[a] *Synergy Ceramics Laboratory, Fine Ceramics Research Association (FCRA), Nagoya 463-8687, Japan*
[b] *Synergy Materials Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Nagoya 463-8687, Japan*
[c] *Nissan Research Center, Nissan Motor Co., Ltd., Yokosuka 237-8523, Japan*

Received 2 September 2002; received in revised form 17 December 2002; accepted 17 December 2002

Abstract

It has recently been identified that controlled porosity on a tribological surface can contribute to friction reduction at sliding contact interfaces. One of the presumed effects of surface texturing under boundary lubrication conditions is that micro-dimples can act as fluid reservoirs and play a role in promoting the retention of a lubricating film. The present paper verifies the effect of micro-dimples on the frictional properties of a silicon nitride ceramic mated with hardened steel. Pin-on-disk tests modeling the contact between cylindrical and planar faces were carried out for a variety of surface morphologies in which dimples were pattern machined with different size, density, and geometry. Compared to a lapped smooth surface without texturing, some samples successfully realized reductions in friction coefficient from 0.12 to 0.10. It was found that the tribological characteristics depended greatly on the size and density of the micro-dimples, whilst the dimple shape did not significantly affect the friction coefficient regardless of rounded or angular profiles. A dimple size of approximately 100 μm at a density of 5–20% is recommended.

Keywords: Friction coefficient; Friction reduction; Silicon nitride ceramic; Surface texturing

1. Introduction

It is known that engine friction loss accounts for 40% of the total energy developed by a typical automotive engine [1]. Reduction of friction is therefore considered to be a necessary requirement for improved fuel consumption, which is desirable in terms of both environmental protection as well as customer satisfaction.

The improvement of surface finish is one of the most reasonable methods of reducing friction, and has therefore promoted the increase in the number of automotive components whose surfaces are finished with grinding and subsequent additional processes such as lapping or superfinishing [2,3]. It is expected that, although this tendency is considered to continue increasing, the achievable surface roughness will ultimately be limited by the material and machining principles.

Surface texturing is another attractive approach for the application of sliding contact elements [4–6]. Shallow pores artificially distributed on a frictional surface are expected to act as fluid reservoirs and help to promote the retention of a lubricating thin film between mating components. In addition, in instances where there are frequent start/stop operations, it is thought that the lubricant remaining in the pores can avoid an abnormal temperature rise caused by dry running conditions. Most of the previous applications of surface texturing have been directed at those situations in which the contact is planar-to-planar, and therefore have a relatively large frictional interface, such as mechanical face seals [7,8] and strip drawing [9]. This is attributed to the fact that micro-dimples are expected to function mainly in hydrodynamic lubrication conditions. Due to the fact that there are still very few examples of attempting to reduce friction in boundary lubrication conditions with high contact pressure such as cam/follower combination, the effects of surface texturing remain unknown.

Advanced ceramics are often utilized for tribological components due to their superior mechanical properties such as high hardness and high wear resistance [10]. Silicon nitride is one of the most popular ceramic materials that attract much attention as a structural element for automotive engines. This ceramic has been applied, for example as a cam follower with some beneficial results having being reported [11,12].

* Corresponding author. Present address: Research Prototype and Test Department, Nissan Research Center, Nissan Motor Co., Ltd., Natsushima-Cho 1, Yokosuka 237-8523, Japan. Tel.: +81-46-867-5206.
E-mail address: m-wakuda@mail.nissan.co.jp (M. Wakuda).

0043-1648/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0043-1648(03)00004-8

This paper attempts to clarify the potential of textured micro-dimples on a silicon nitride ceramic plate mated with cylindrical-shaped steel elements. The effects of surface texturing with a variety of dimensions and distributions of micro-dimples are evaluated to acquire a guide to optimal dimple pattern.

2. Experimental procedure

2.1. Testing method and test conditions

Friction tests employed a unique pin-on-disk tester, which is shown schematically in Fig. 1. This testing machine was specially designed for modeling the sliding line contact between a cylindrical and planar interface such as that observed in the cam/follower combination. A set of three pins was installed into a metallic holder, and fixed such that they could not rotate themselves. The hardened steel pins had dimensions of 5 mm in diameter and 5 mm in length and a surface roughness of R_a 0.04 μm. The center of the pin holder was loaded in the direction normal to a ceramic plate located beneath the pins, and which was rotating at a given speed.

Friction test conditions are listed in Table 1. Assuming the combination of steel pins and a silicon nitride ceramic plate, the maximum given load of 490 N corresponded to a high contact pressure of 0.78 GPa, matching the cam/follower application. The sliding contact zone was fully soaked in lubricant, typical engine oil (5W30SJ) including zinc dialkyl-dithiophosphate (ZnDTP). The temperature was kept at 80 °C throughout the tests, and the viscosity of the lubricant oil was 0.0136 Pa s at the tested temperature.

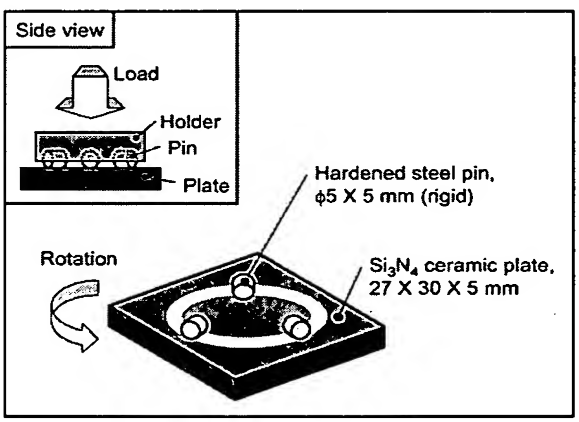

Fig. 1. Schematic diagram of pin-on-disk friction testing method. The three pins are prevented from rotating themselves by location in a metal holder.

Table 1
Conditions of pin-on-disk testing

Pin	Hardened steel
Disk	Hot-pressed silicon nitride
Load (N)	98–490
Sliding velocity (m/s)	0.012–1.2
Rotational radius (mm)	11
Lubricant	Engine oil (5W30SJ)
Temperature (°C)	80

Table 2
Material properties of tested silicon nitride ceramic

Density (g/cm^3)	3.24
Vickers hardness (HV)	1600
Flexural strength (MPa)	1000
Fracture toughness K_{IC} (MPa m$^{1/2}$)	5.4

Friction coefficients were calculated using the friction torque measured at different rotational speeds of the plate between 10 and 1000 min^{-1}. The frictional radius was 11 mm, such that these plate speeds corresponded to 0.012–1.2 m/s. The lubricating film thickness theoretically derived for a sliding velocity of 1.2 m/s was approximately 0.04 μm. This value was equivalent to, or lower than the surface roughness (peak-to-valley height) of the pins and plate, which meant that the test conditions existed within a boundary lubrication range.

In order to avoid initial unstable conditions, each friction test was carried out following a running-in operation with a normal load of 490 N, a sliding velocity of 0.035 m/s, and duration of 10 min.

2.2. Variation of surface textured samples

The ceramic material used was typical hot-pressed silicon nitride, fired with sintering additives of 5 wt.% yttria and 2 wt.% alumina. Representative mechanical properties of the bulk material are shown in Table 2. Prior to surface texturing, the sample surfaces were finished by lapping using first 3 and then 0.5 μm diamond pastes. The surface roughness following the lapping process was less than $R_a = 0.01$ μm.

Subsequent micro-dimpling was performed with either abrasive jet machining (AJM) or excimer laser beam

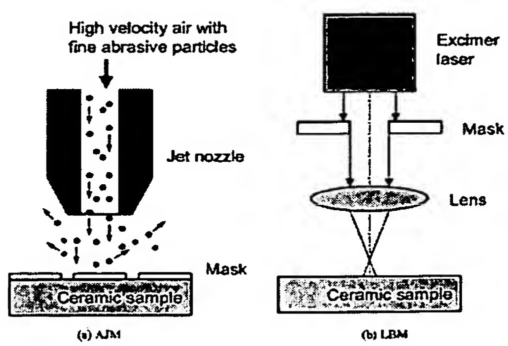

Fig. 2. The two methods for micro-dimpling of a ceramic plate.

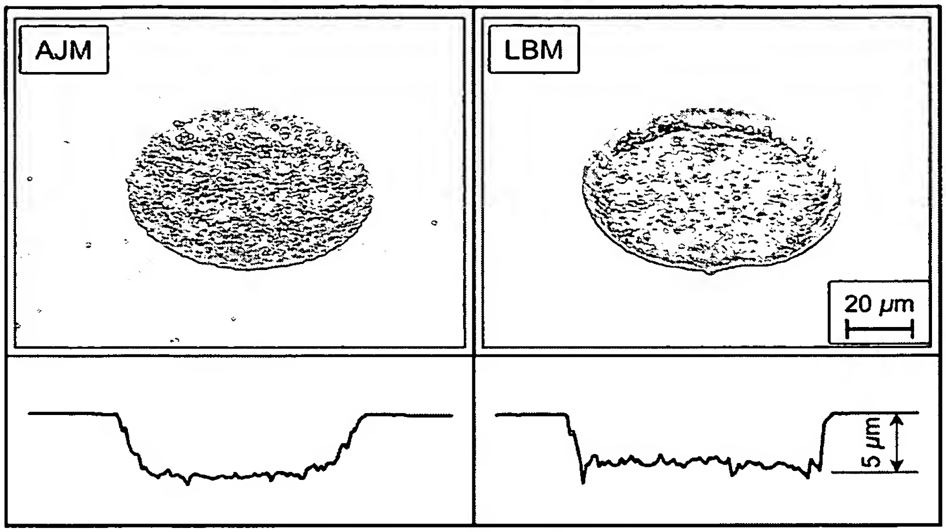

Fig. 3. Appearance of micro-dimples produced by AJM and LBM, both of which exhibited characteristic profiles.

machining (LBM) in the manners shown in Fig. 2. The two micro-machining methods resulted in totally different dimple profiles, in other words. Dimples produced by the AJM process had a spherical morphology, while the LBM process led to rather angular dimples as illustrated in Fig. 3 [13]. With micro-machining of metals, build up of material often occurs around the dimples as a result of plastic deformation. In contrast, the surface of the ceramic samples in the areas around the dimples remained smooth, such that no deburring process was required.

Micro-dimples with a variety of dimensions and distributions were pattern machined on to the sample surface by AJM or LBM. The dimple size was set at 40, 80, or 120 μm in diameter and area densities of 7.5, 15, and 30%. An example of the textured surface morphology is shown in Fig. 4. The dimple depth was 5 μm for all the dimples.

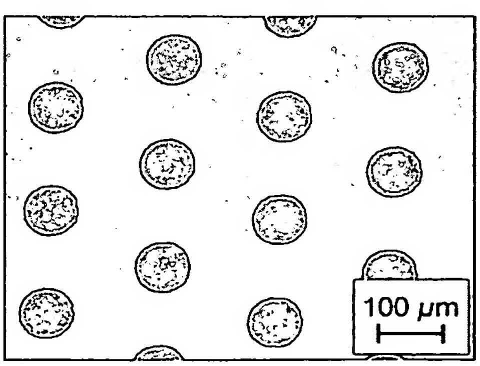

Fig. 4. An example of a micro-dimpling pattern. In this example, 80 μm dimples were distributed with a density of 15%.

3. Experimental results

3.1. *Influence of dimple pattern on frictional properties*

Friction tests were first carried out at a constant normal load of 490 N for various textured surface morphologies. The friction coefficient was measured at different sliding velocities between 0.012 and 1.2 m/s, following the running-in period. The surface roughness of both the pins and the plates showed no obvious change following the friction test.

The relationship between the sliding velocity and friction coefficient for the sample with no dimples is shown in Fig. 5. Typical of friction behavior under boundary lubrication conditions, an increase of sliding velocity resulted in a gradual decrease in the friction coefficient. The friction coefficient at the very low sliding velocity was approximately 0.11.

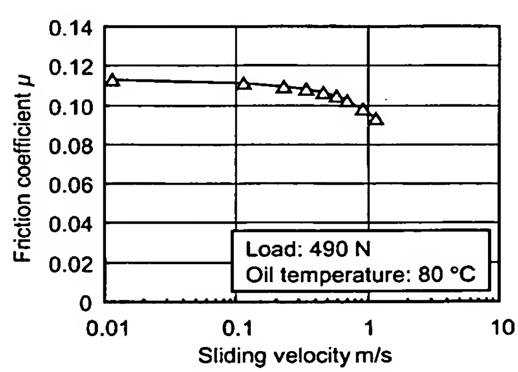

Fig. 5. Frictional properties of the non-textured ceramic plates for different sliding velocities.

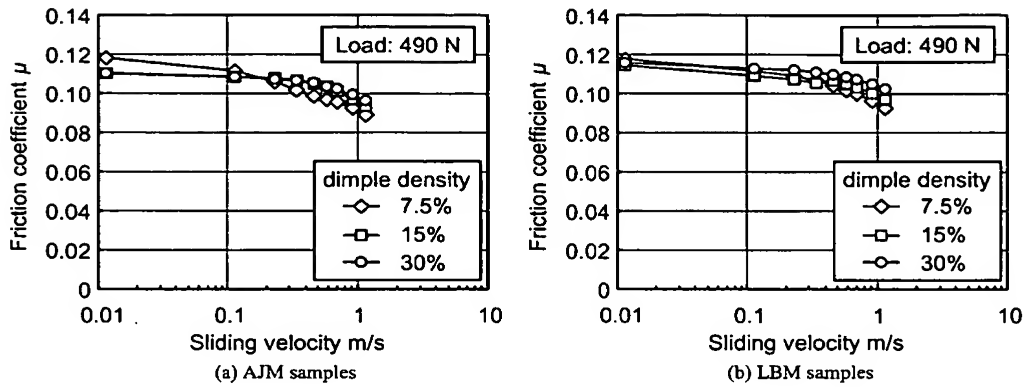

Fig. 6. Frictional properties for different sliding velocities of the ceramic plates textured with 40 μm dimples.

Under the conditions where the velocity was over 0.8 m/s, the friction coefficient was reduced to below 0.10.

The frictional properties of the samples with the 40 μm dimples at different densities are shown in Fig. 6. Almost all of the textured samples exhibited similar curves to that of the non-textured. The result demonstrated that micro-dimpling led to no apparent benefits in frictional properties with this particular dimple size. The scale of micro-dimples was too small to function as fluid reservoirs capable of increasing the loading capacity and/or promoting the retention of a lubricating film. In addition, an increase of the dimple density alone, resulting in a decrease of the direct contact area, cannot affect the frictional properties.

The test results for the samples with 80 μm dimples are illustrated in Fig. 7. For the cases where the dimple density was 7.5 and 15%, machined by both the AJM and LBM processes, reduced friction coefficients were successfully realized over the entire range of the tested sliding velocity. In the case of a dimple density of 15%, in particular, obvious friction reduction was also attained at the very low sliding velocity range of around 0.01 m/s, which can contribute to the avoidance of an abnormal temperature rise in start/stop motions. It was thus verified that surface texturing has a great potential for reducing friction in boundary lubrication conditions, if the micro-dimples are distributed in an appropriate pattern. In contrast, in the case of a dimple density of 30% textured by both AJM and LBM, friction coefficients were slightly higher than those for the non-dimpled sample. This is thought to be due to the fact as the area of the surface taken up by the dimples increases with dimple density, the actual contact surface is decreased leading to an increase of the actual contact pressure at the sliding interface, which produced a negative effect on the frictional properties.

The results for the samples with 120 μm dimples are shown in Fig. 8. Dramatic friction reduction was attained for the samples with dimple densities of 7.5 and 15%, in particular. With these dimpling patterns the reduction in friction coefficient compared to the non-dimpled surface was approximately 20%. In addition, slight friction reduction was also achieved in the case of the 30% density of dimples, despite the above-described negative effect. It is thought that the beneficial effect of micro-dimples becomes larger with an increase of the dimple size.

These test results are summarized in Fig. 9, showing the friction coefficient of the textured surfaces at representative test conditions of 1.2 m/s sliding speed and normal load of

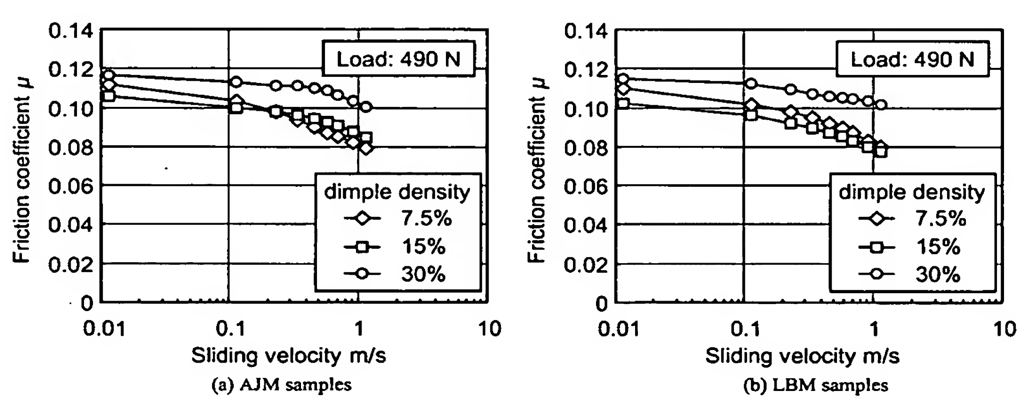

Fig. 7. Frictional properties for different sliding velocities of the ceramic plates textured with 80 μm dimples.

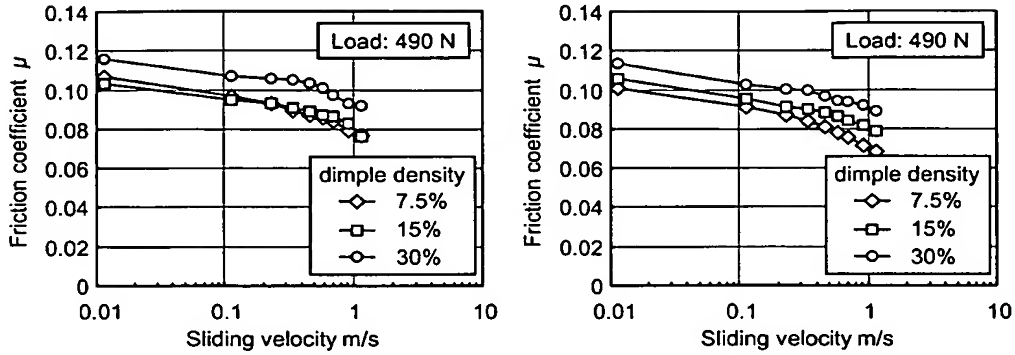

Fig. 8. Frictional properties for different sliding velocities of the ceramic plates textured with 120 μm dimples.

490 N. The friction coefficient of the non-textured surface is shown with a broken line. This figure implies that proper texturing of micro-dimples can succeed in friction reduction. Despite expectations to the contrary, the dimple geometry was not critical regardless of rounded or angular profiles. The appropriate dimple density is thought to be in the range of 5–20%. As shown for the samples with a dimple density of 30%, a higher dimple density, and therefore a decrease in the direct contact area between mating elements in boundary lubrication conditions, does not always produce good results. In addition to the dimple density, dimple size is another predominant factor for reducing friction. Texturing with 40 μm dimples had no beneficial effect on friction reduction under the above test conditions, whilst lower friction coefficients were obtained for the larger dimples.

The influence of the dimple size on frictional properties was investigated by considering the relationship between the size of the dimple and the width of the contact line between the pins and ceramic plate. Theoretically, an initial point contact would result in the pin tracing a line of negligible width on the ceramic plate during the sliding contact. Strictly speaking, however, the contact interface between mating elements formed a narrow rectangular area, whose width would depend on the normal load. According to calculations based on the Hertzian stress theory, the contact line width was 54 μm for the above test load of 490 N. Consequently, for the case of 40 μm dimples, as shown in Fig. 10, the contact area fully encompassed the dimples. However, for the 80 and 120 μm sizes the dimples always straddled the contact zone. Therefore, an additional test was carried out where the normal load was varied between 98 and 490 N, such that there was a wide variation in the width of the contact area.

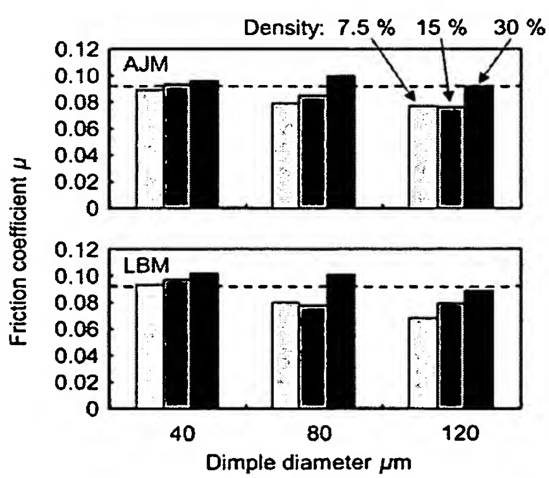

Fig. 9. Comparison of friction coefficient of the textured surfaces.

The frictional properties for the different normal loads are shown in Fig. 11. In this experiment, three samples textured with dimples of different sizes at 15% density by AJM were evaluated in addition to the non-dimpled sample. The sliding velocity was fixed at 1.2 m/s. The friction coefficient decreased with a decrease in the load for all the samples, which is typical behavior for the friction conditions of the boundary to mixed lubrication modes. The important point to notice from this figure is that the curve of the 40 μm dimpled sample deviated from that of the non-dimpled sample below loads of approximately 300 N. The theoretical calculation demonstrated that the contact width equaled 40 μm at a normal load of 270 N. This fact implies that only dimples with a diameter larger than the contact width can affect the friction reduction, when subjected to the line contact sliding friction.

In order to generalize the effect of the size of dimple relative to that of the contact width, the above test results are re-plotted in Fig. 12. In this figure the specific friction coefficient, normalized by that of the non-dimpled sample at the same friction conditions, is plotted against the ratio of dimple size to contact width. This contact width is a value calculated from Hertzian stress theory for each test condition. These theoretical values were used since the wear scar width on the pins was not measurable even after the friction test with high contact pressure.

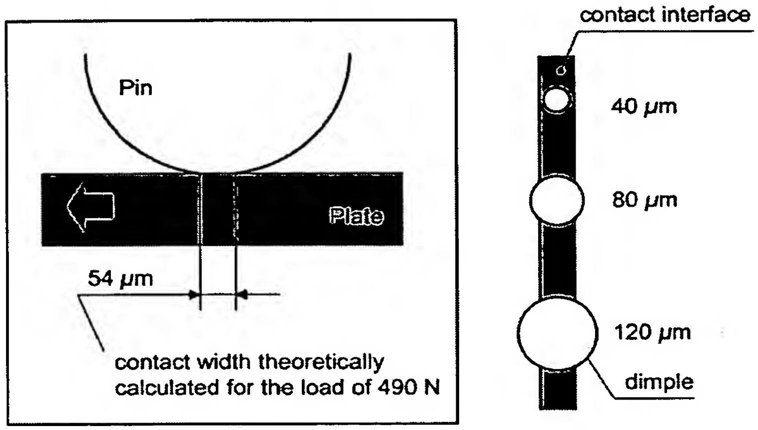

Fig. 10. Relationship between contact width of mating elements and dimple size.

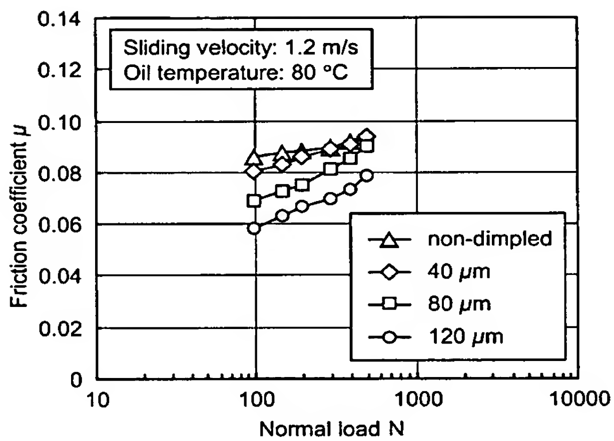

Fig. 11. Frictional properties of the ceramic plates for different normal loads.

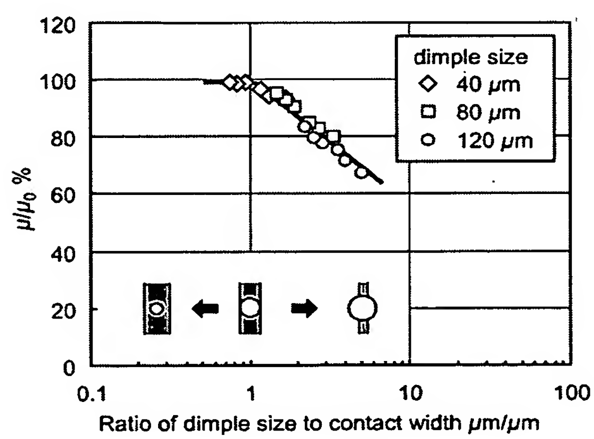

Fig. 12. Effect of the ratio of dimple size to contact width on friction reduction. The specific friction coefficient was calculated by normalizing to the friction coefficient of the non-dimpled surface.

For ratios less than 1 the normalized friction coefficient was 100% (no effect on friction reduction). However, for ratios greater than 1 the value decreased linearly. This implies that the dimple size relative to the contact width is an important factor in determining the frictional properties, and the effect of texturing on friction reduction has a linear relation with this parameter in the tested range. Therefore, the dimple size should be selected so as to be sufficiently large when compared to the contact width calculated theoretically from the friction conditions. Within the tested conditions, the larger the dimple size, the larger the effect of texturing on friction reduction. On the other hand, a large effect on the friction reduction cannot be expected using a textured surface with small dimples when they are of the same order as the contact width at the sliding contact interface.

3.2. Lubricating performance of textured surface

In order to assess the effectiveness of the texturing over prolonged periods, changes in the friction coefficient under

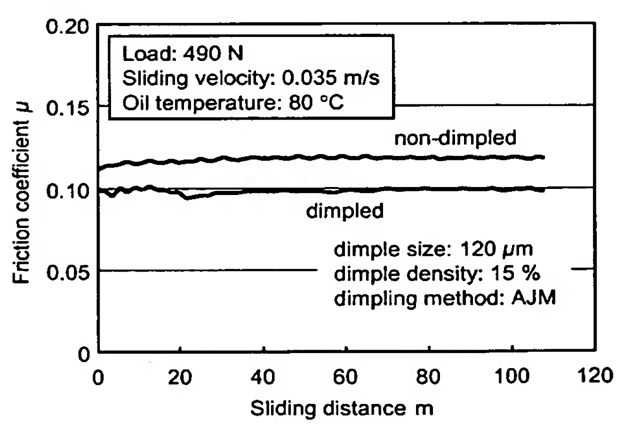

Fig. 13. Changes in friction coefficient under long sliding conditions.

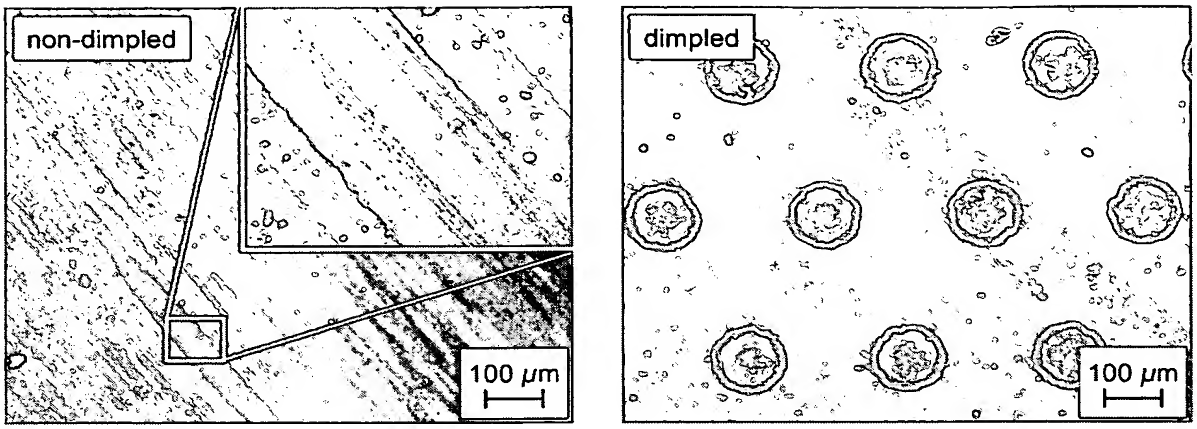

Fig. 14. SEM observation of the friction surface following the long sliding test.

longer sliding conditions were evaluated using two samples; one was the non-dimpled and the other was one of the most effective morphologies, 120 μm dimples at a density of 15% by AJM. The test was performed under the same friction conditions as those of the running-in operation, but for a longer period of 60 min. Considering the cam/follower application these test conditions were much more severe than those for an idling operation of typical passenger car engines, in that the tested sliding velocity was almost one order of magnitude lower.

As shown in Fig. 13, the difference in the friction coefficient between the two samples was distinct. The friction coefficient of the non-dimpled sample initially was 0.114 and, following a slight increase at the beginning of the test, remained relatively stable value of around 0.12 thereafter. In contrast, the textured surface morphology attained a low, stable, friction coefficient of around 0.10 throughout the long sliding test. This value was approximately 20% lower than that of the non-dimpled sample.

Following this sliding test, the possibility of tribochemical reactions at the friction surface was microscopically analyzed for the two samples as shown in Fig. 14. An SEM observation of the non-dimpled surface at high magnification clearly clarified that the friction track was covered with a very thin tribofilm. This kind of film, being accompanied with frictional streaks, was observed only for the non-dimpled sample, but the plateau face of the dimpled sample had very few chemical or mechanical changes.

The EDX spectrum shown in Fig. 15 verified that the thin film was composed mainly of the elements of Zn, P, and S, which originated from the components of ZnDTP. These elements were absorbed from the lubricant oil as a result of the direct contact between the mating components under the very high contact pressure. The formation of such undesirable tribochemical thin films is thought to be a critical reason for the gradual increase in the friction coefficient at the early stage of the test [14,15]. The amount of film increased up until a sliding distance of approximately 20 m, and then remained stable. On the other hand, due to the fact that these chemical elements were not detected on the dimpled sample, it was found that surface texturing contributed to a significant improvement of the lubrication performance.

It was thus verified that surface texturing can affect the friction reduction considerably under boundary lubrication conditions, and the effect can be maintained even under longer, more severe sliding contact conditions. Appropriately distributed micro-dimples play an important role in promoting the retention of lubricating thin films, which help to avoid the formation of undesirable tribochemical films.

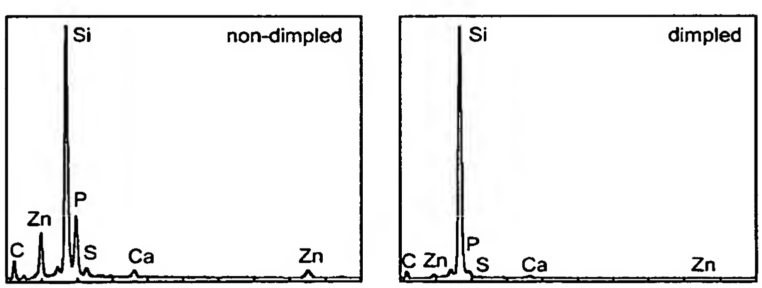

Fig. 15. EDX analysis of absorbed elements following the long sliding friction test. Zn, P, S, and Ca are additive elements in the lubricant oil.

4. Conclusions

Frictional properties of textured ceramic surfaces were assessed through pin-on-disk tests modeling a cylinder/planar contact interface with very high contact pressure. The experimental results played an important role in clarifying the high potential of a micro-texturing technique for reductions in friction at line contact interfaces. The findings are concluded as follows:

(1) It was verified that surface texturing is an effective key to friction reduction. An appropriate surface morphology can lead to dramatic reductions in friction over a wide range, covering boundary to mixed lubrication conditions at the line contact sliding interface.
(2) The effect of textured micro-dimples is retained even under severe friction conditions. A well-lubricated sample with appropriate surface morphology succeeds in reducing the friction coefficient without forming undesirable tribochemical films.
(3) A dimple size of approximately 100 μm is recommended under the tested friction conditions. Micro-dimples, whose scale is equivalent to, or smaller than, the contact line width between the mating elements are not effective. The distribution of micro-dimples is also an important factor. A dimple density of 5–20% is recommended. The dimple geometry has little influence on the frictional properties regardless of rounded or angular profiles.

Acknowledgements

This work has been supported by METI, Japan, as part of the Synergy Ceramics Project. Part of the work has been supported by NEDO. The authors are members of the Joint Research Consortium of Synergy Ceramics. Tested silicon nitride ceramic samples were supplied by Mr. Hideki Hyuga of FCRA, who is also a member of the consortium. Special thanks are due to Dr. Mark I. Jones of AIST for his assistance in rewriting the manuscript with regard to English usage.

References

[1] M. Nakada, Trends in engine technology and tribology, Tribol. Int. 27 (1) (1994) 3–8.
[2] A. Kato, Y. Yasuda, An analysis of friction reduction techniques for the direct-acting valve train system of a new-generation lightweight 3-Liter V6 Nissan engine, SAE Paper No. 940992, 1994.
[3] M. Masuda, M. Ujino, K. Shimoda, K. Nishida, I. Marumoto, Y. Moriyama, Development of titanium nitride coated shim for a direct acting OHC engine, SAE Paper No. 970002, 1997.
[4] A. Blatter, M. Maillat, S.M. Pimenov, G.A. Shafeev, A.V. Simakin, E.N. Loubnin, Lubricated sliding performance of laser-patterned sapphire, Wear 232 (1999) 226–230.
[5] A. Ronen, I. Etsion, Y. Kligerman, Friction-reducing surface-texturing in reciprocating automotive components, Tribol. Trans. 44 (3) (2001) 359–366.
[6] X. Wang, K. Kato, K. Adachi, K. Aizawa, The effect of laser texturing of SiC surface on the critical load for the transition of water lubrication mode from hydrodynamic to mixed, Tribol. Int. 34 (2001) 703–711.
[7] X.Q. Yu, S. He, R.L. Cai, Frictional characteristics of mechanical seals with a laser-textured seal face, J. Mater. Process. Technol. 129 (2002) 463–466.
[8] Y. Klingerman, I. Etsion, Analysis of the hydrodynamic effects in a surface textured circumferential gas seal, Tribol. Trans. 44 (3) (2001) 472–478.
[9] I. Shimizu, J.L. Andreasen, J.I. Bech, N. Bay, Influence of work-piece surface topography on the mechanisms of liquid lubrication in strip drawing, Trans. ASME J. Tribol. 123 (4) (2001) 290–294.
[10] M. Woydt, K.-H. Habig, On the tribology of ceramic materials in closed systems, Ceram. Forum Int. 66 (5/6) (1989) 198–207.
[11] S. Matsumoto, S. Maeda, K. Kimura, M. Taniguchi, Development of an inexpensive, highly wear-resistant ceramic cam follower. Part 1. Engine test results, SAE Paper No. 931933, 1993.
[12] K. Kitamura, H. Takebayashi, M. Ikeda, H.M. Percoulis, Development of ceramic cam roller follower for engine application, SAE Paper No. 972774, 1997.
[13] M. Wakuda, Y. Yamauchi, S. Kanzaki, Influence of micromachining on strength degradation of silicon nitride ceramic, J. Manuf. Eng. B 216 (1) (2002) 55–60.
[14] G. Tripaldi, A. Vettor, H. Spikes, Friction behavior of ZDDP films in the mixed, boundary/EHD regime, SAE Paper No. 962036, 1996, pp. 73–84.
[15] Y. Mabuchi, M. Kano, T. Ishikawa, A. Sano, T. Wakizono, The effect of ZDDP additive in CVT fluid on increasing friction coefficient between belt elements and pulleys of belt-drive continuously variable transmissions, Tribol. Trans. 43 (2) (2000) 229–236.